Cahiers de géographie du Québec

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Volume 3, numéro 6, 1959

Mélanges géographiques canadiens offerts à Raoul Blanchard

URI : https://id.erudit.org/iderudit/020176ar
DOI : https://doi.org/10.7202/020176ar

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Éditeur(s)

Département de géographie de l'Université Laval

ISSN

0007-9766 (imprimé)
1708-8968 (numérique)

Découvrir la revue

Citer cet article

Hare, K. (1959). The circumpolar atmospheric circulation in high latitudes. *Cahiers de géographie du Québec*, *3*(6), 163–178. https://doi.org/10.7202/020176ar

THE CIRCUMPOLAR ATMOSPHERIC CIRCULATION IN HIGH LATITUDES

by

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Prologue

The writer must apologize for injecting into a volume of geographical studies an article with so alien a title. The editors of the *Mélanges*, however, made it clear that they preferred to receive contributions derived from the current research of the selected authors — and at present the writer is mainly engaged in studies of the arctic atmosphere. The study of world climate, in itself a usual activity for a geographer, requires a thorough understanding of the general circulation of the atmosphere (and to some extent of the oceans). In high latitudes, the circulation has only recently become accessible to such study, since the observational network is very young. Hence the climatologist who elects to concentrate on northern regions must spend much of his time trying to comprehend the present-day circulation.

There can be few fields of research that draw together so many different disciplines as the study of climate, and especially of climatic change. Close relationships exist between climate and many other natural or cultural phenomena. The distribution of northern vegetation, for example, has depended on the fluctuating climates of the arctic and sub-arctic belts — a selective process that has operated ruthlessly ever since Miocene times. The biologists concerned with these relations — such as von Post and Godwin in Europe, Potzger, Courtemanche, Deevey and Cain in North America — have taught us far more about the facts of post-glacial climatic change than has any meteorologist. There is also a strong interest among pre-historians ; the rapid cultural evolution of Middle Eastern societies in the seven millenia B. C. was accompanied by the intermittent dessication of the area, and the subsequent spread of these cultures across Europe was obviously influenced by the changes of climate. Hence the student of the northern climates finds himself rubbing shoulders with specialists from many diverse disciplines.

Among this group, meteorologists have hitherto been few in number. They can do their work, only if an adequate network of synoptic observing stations exists and can be maintained for some years. Until the end of world War II this condition had never been met, even during the two International Polar Years. Hence pre-1940 meteorological opinion about the arctic climate, as guided by the pioneer workers in the field — Harald Sverdrup, Franz Baur and the Russian Dzerdzeyevsky — was based on ingenious inference from inadequate data, rather than on detailed synthesis. Moreover, the picture that emerged from these studies was mainly one of the surface circulation ; only rudimentary upper air studies could be made. Thus in the ten years following 1939, when C. G. Rossby published his revolutionary paper on the wave-structure of the circumpolar westerlies,[1] arctic meteorology stood still at a time when the science as a whole was striding forward into the aerological age — i.e., the systematic exploration of the upper air.

The writer considers that the causes of climatic change cannot possibly be discovered until we understand the controls of present-day world climate. In effect, this is the meteorological equivalent of the geologists' principle of uniformitarianism. We have no choice but to argue back into the past from the standpoint of our own experience. And at present there is no adequate *theory* of world climate from which we can so argue. Since 1949, we have made great strides in this direction. From the physical standpoint, Budyko [2] and his numerous Russian colleagues have made notable advances towards an understanding of the energy exchanges at the surface of the earth — how the solar energy is converted to other forms, and so made available to drive the atmospheric circulation. Thornthwaite's group [3] in the U.S. have done likewise for the related question of the balance. Several other groups — under Gjerknes [4] and Starr [5] in the U.S., and Flohn [6] in Germany — have similarly advanced towards a fuller comprehension of the general circulation of the atmosphere ; these workers have attempted to show how that circulation transports heat, momentum and water vapour polewards from the tropical source regions. In spite of all this, however, the writer doubts whether any meteorologist, however skilled, could predict in any detail the consequences of a sudden change in the output of solar energy, or of the earth's manner of receiving it. Hence it seems to him unlikely that anyone can yet hope to establish an adequate theory of climatic change.

The remedy lies, in the writer's view, in intensive study of the present-day climates in both their dynamical and physical aspects. His own work, since 1954, has been directed at the north polar cap — with the limits not rigorously defined — on the grounds that such a study is likely to contribute towards a general theory of climatic change ; for it has been the expansion and contraction of these north polar climates that have marked the Pleistocene epoch, and to some extent the entire Tertiary period. Such a study cannot, however, proceed *in vacuo* ; in all probability, the transfer northwards of heat and moisture from the tropics is equally vital.

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[1] Rossby, C. G., and collaborators, *Relation between variations in the intensity of the zonal circulation of the atmosphere and the displacement of the semi-permanent centres of action*, in *J. Marine Research*, 1939, vol. 2, pp. 38-55.

[2] Budyke, M., *The heat balance of the earth's surface*, in *Gidrometeeizdat Leningrad*, 1956, 255 pp., translated by N. A. Stepaneva, PB 131692, Office of Technical Services, U.S. Department of Commerce, Washington, 1958, 259 pp.

[3] Thornthwaite, C. W., and Mather, J. R., *The water balance*, in *Publications in Climatology*, Laboratory of Climatology, Drexel Institute of Technology, 1955, vol. VIII, pp. 1-86.

[4] Bjerknes, J., editor, *Large-scale synoptic processes*, Final Report, Contract AF 19 (604) — 1286, University of California at Los Angeles, 1957.

[5] Starr, V. P., see for example *The physical basis for the general circulation*, in *Compendium of meteorology*, American Meteorological Society, Boston, 1951, pp. 541-550.

[6] Flohn, H., many papers, of which for example see *Zur Aerologie der Polargebiete*, in *Meteorologisches Rundschau*, 1952, vol. 5, pp. 81-87 and 121-128. See also reference 10.

The following account deals with some of the more interesting recent discoveries made in the north, especially in the upper air. The approach is descriptive and non-technical, since it was thought likely that this volume will be read primarily by non-meteorologists. A comprehensive review of existing knowledge on the arctic circulation has been published elsewhere by Hare and Orvig.[7]

Aerological exploration

Since World War II there has been a progressive increase in the number of weather stations in the arctic and sub-arctic. In the more remote areas, most of these stations include in their duties twice-daily soundings of the temperature, humidity and wind fields of the upper atmosphere, often to heights above 70,000 ft., and sometimes to as much as 100,000 ft. Since 1952, when Ice Island T-3 was first occupied, there have been regular soundings from the heart of the polar pack-ice — from which we had hitherto received only the reports of drifting ships or pack-ice expeditions. The network is not yet adequate for detailed dynamical analysis, but it is now possible to draw reasonably good synoptic charts entirely round the pole for levels as high as 50,000 ft., and for part of the area to as high as 80,000 ft. Figure I shows the distribution of upper air sounding stations whose reports were being received at the Central Analysis Office, Dorval Airport, in the autumn of 1958. It will be noted that data are received from the U.S.S.R. in considerable quantities.

The first fruits of this activity have included fairly reliable weather maps over the entire arctic. Circumpolar analysis is conducted in several North American and European centres at sea-level, 700 mb (roughly 10,000 ft.) and 500 mb (roughly 18,000 ft.). At the Canadian Central Analysis Office, Montréal Airport, daily analysis is carried out by the writer and his colleagues of the Arctic Meteorology Research Group at 200 mb. (about 40,000 ft.) and 100 mb. (about 53,000 ft.) over an area extending from mid-Pacific across North America to European Russia, and from 30°N. to the pole. Over North America itself, the Group also analyzes at the 25 mb. level (82,000 ft.).

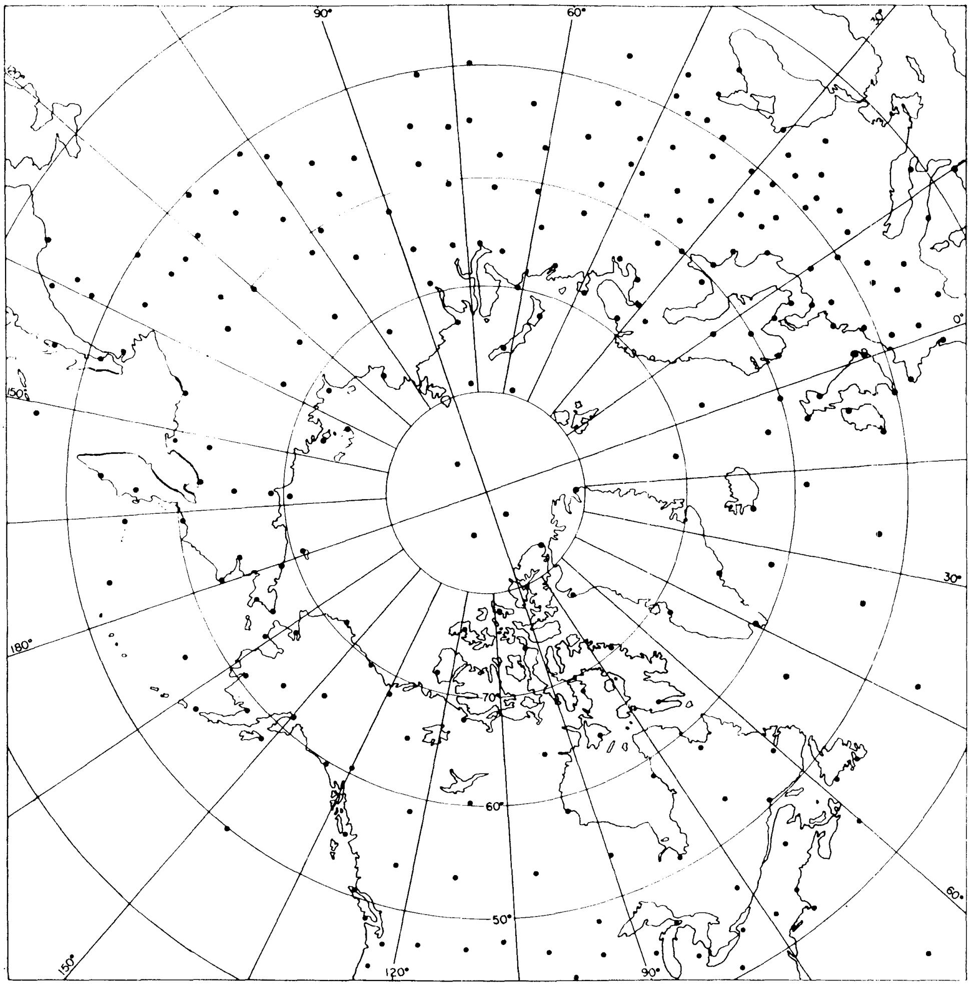
The observational picture has thus been revolutionized. Ten years ago, even surface analysis was largely conjecture ; today, reasonably controlled weather maps can be drawn as high as the middle stratosphere. From these maps, and from the wind and temperature data accumulating in the climatological files of the weather services, one can already gain a credible précis of the mean thermal structure and circulation of the entire arctic atmosphere below about 82,000 ft. Moreover, one can now speak with authority about the nature, frequency and distribution of the weather disturbances affecting the north. It emerges that these are for the most part deep-seated systems, having their strongest development far above the ground level. The account given by the present writer only three years ago is already out of date, since it is concerned

[7] Hare, F. K., and Orvig, S., *The Arctic circulation*, in *Arctic Meteorology Research Group Publications in Meteorology*, 1958, No. 12, 211 pp.

only with events near ground-level — where, on the whole, the arctic atmosphere is least interesting.[8]

One prime result of these advances has been the realization that the dominant arctic circulations are great circumpolar vortices, extending from 5,000

FIGURE I



Network of stations from which twice daily, upper air reports were being received at Montréal Airport, Autumn 1958.

to 7,000 feet up to the higher stratosphere — to well above 100,000 feet. The surface pressure systems of the geographers' textbooks — the Aleutian and

[8] HARE, F. K., *Weather and climate*, Chapter 4, in *Geography of the Northlands*, ed. G.H.T. Kimble and D. Good, American Geographical Society, New York, 1955.

Icelandic lows, the Siberian high, etc., — are shallow affairs, probably dependent for their existence almost wholly on the effect on the upper flow of the distribution of land and water (or ice), with the attendant variability in continentality, and of the accidental emplacement of the main mountain systems. The surface systems are of great consequence when one seeks to explain surface climates. Increasingly we realize, however, that their variability in position and intensity — critical in studies of climatic change — depends on the behaviour of the circumpolar vortices at higher levels. To these upper systems, then, it is now logical to devote one's energies.

The Ferrel vortex

Throughout the year the mean flow of the middle and upper troposphere — the layers in which temperature decreases with height in the familiar fashion — is a vast, circumpolar vortex of westerly winds about a cyclonic low pressure centre or centres near the Pole itself. These westerlies have, of course, been known in mid-latitudes for a century or more. They were first described by Ferrel,[9] who believed that they extended at sea-level to the pole. Later it was first inferred and then observationally proved that they extend to a polar cyclone only in the middle and upper troposphere. In the lower atmosphere — below about 7,000 ft., — higher pressure tends to occur near the pole, with light easterlies along its southern flank. Nevertheless, the circumpolar westerlies of the higher levels are still referred to by many meteorologists as the Ferrel vortex.

Figure II gives a sketch of the mean flow at various levels over the north polar area in mid-winter (January). At this time of year, the whole arctic atmosphere is in darkness, and cools radiatively to very low temperatures. Consequently the westerlies increase with height. At the lower levels — below about 25,000 ft., roughly the base of the stratosphere — the whirl is triple-centred, with centres over the Canadian Arctic, near Cape Chelyuskin and over N.E. Siberia. In the stratosphere, however — see Figure II — the centre is simple, and is not far from the geographical pole. Figure III shows the strength of the west wind over Alaska and Greenland to confirm these facts. It will be noted that the increase of the circumpolar flow is accentuated above 65,000 ft. This upper vortex is called the *polar-night vortex*, and will be discussed later.

In spring and summer, the flow around the pole slackens considerably, and is more intermittent. Figure IV shows, however, that the vortex still exists in July, though it is simpler and less vigorous than that for January. The flow increases upwards to the tropopause — the level separating troposphere from stratosphere — and then, in striking contrast to winter, *decreases* in the stratosphere. At 65,000 feet it has vanished entirely, and the entire arctic stratosphere lacks any significant flow ; average wind-speeds at this level are no more than 10-15 mph., and directions are almost random. Figure V confirms these statements.

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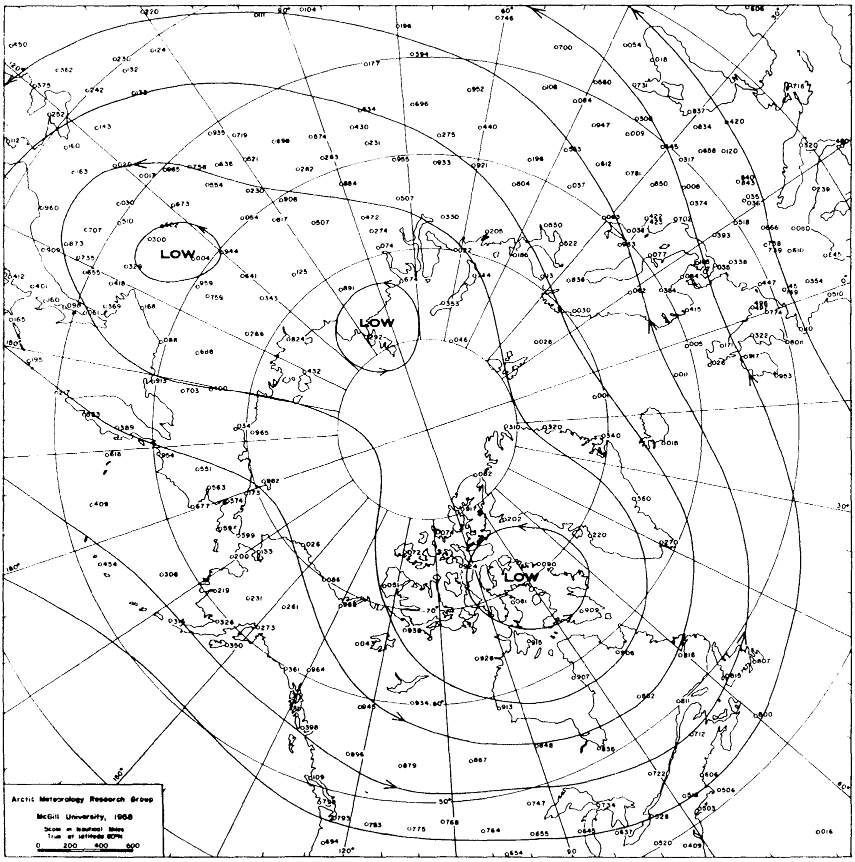
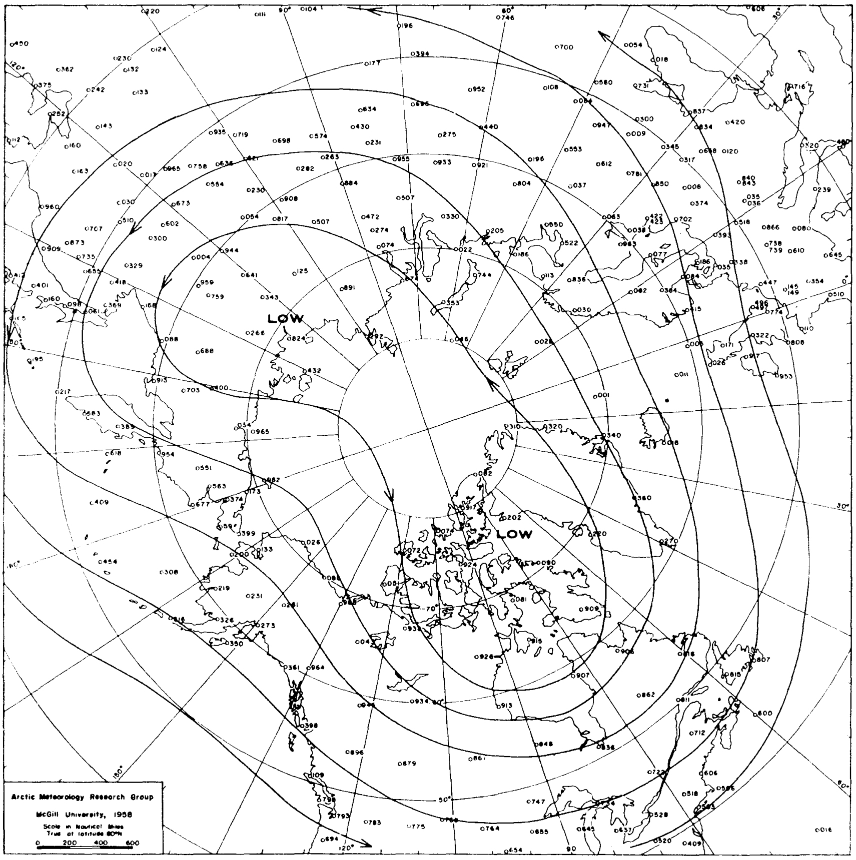
[9] Ferrel, W. A., *A popular treatise on the winds*, New York, Wiley and Sons, 1889.

JANUARY MID-TROPOSPHERE
(15,000 to 20,000 ft)



I

JANUARY LOWER STRATOSPHERE
(30,000 ft 45,000 ft)



II

FIGURE II

Sketches of the mean-flow-patterns of the Arctic atmosphere (mid-winter)

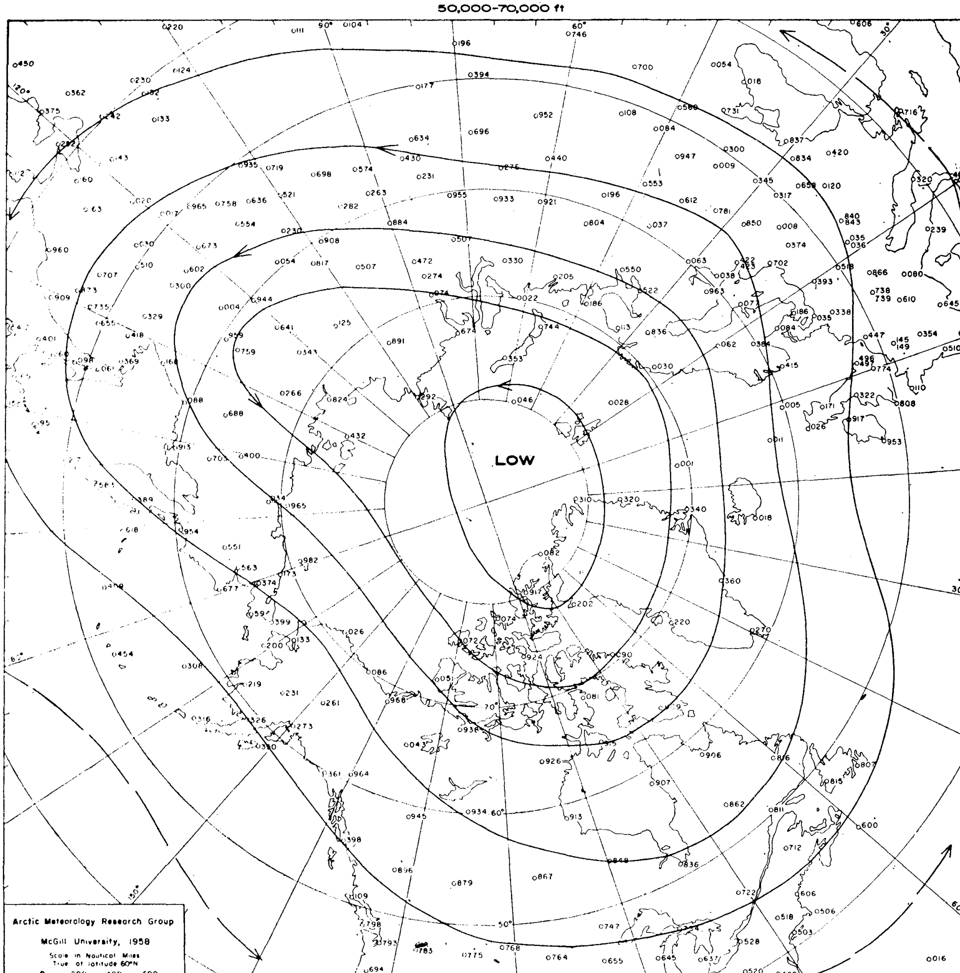
I. Middle Troposphere (15 – 20,000 feet)
II. Lower Stratosphere (30 – 45,000 feet)
III. Middle-Stratosphere (50 – 70,000 feet)

The spacing of the stream-lines is roughly proportional to the mean speed. The diagrams show the Ferrel vortex (1) and the polar night vortex (3). Level 2 represents the transition layer between the two.
Based on original studies by Nameas, Heastie, Scherhag, and Hare and Orvig (1958).

What is the explanation of this dramatic annual change? The clue lies in the so-called thermal wind effect. It can be shown theoretically that a west wind *increases* with height if there is cooler air to the north, and *decreases* if there is warmer air to the north. Throughout the year, the arctic is cooler than mid-latitudes in the troposphere — i.e., below about 25,000 ft. Hence the Ferrel

JANUARY MIDDLE STRATOSPHERE

50,000–70,000 ft

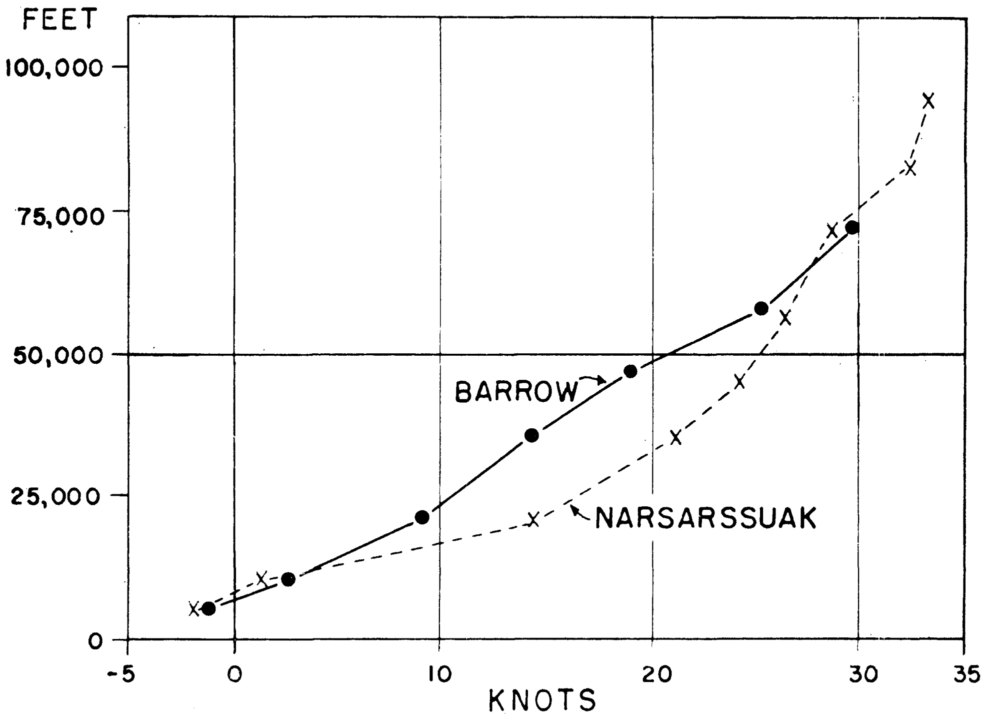


III

vortex increases in strength with height at all seasons to this level. In the stratosphere, however, the thermal structure is quite different. Figure VI shows the temperature distribution very roughly. It will be seen that in winter both the tropical and the polar stratospheres are cold, whereas there is comparative warmth in mid-latitudes (55°N.). Hence the westerlies increase with height polewards of this latitude, and the Ferrel vortex is very high in extent. In summer, however, the arctic stratosphere is relatively warm and hence the vortex decreases upwards in strength.

The great seasonal range of temperature in the arctic stratosphere is a recent discovery. In mid-winter, temperature often falls below $-90°$F., and may attain $-110°$F. ; in the antarctic it has fallen at these levels to $-135°$F. In summer, however, the temperature rises to $-40°$F. or above, so that an annual

FIGURE III



Strength of the circumpolar westerlies over Barrow (71°N.), Alaska, and Narsarssuak (61°N.), Greenland, in winter. As measured by radio-tracked sounding balloons. N. B. Negative values indicate easterly winds.

range of 50° to 70°F. is typical. The north polar area is thus 40° to 50°F. *warmer* in summer at some levels than is the equatorial belt.

This remarkable fact arises from the radiative behaviour of the stratosphere. The warmth of summer arises mainly from the presence of ozone (O^3) in the stratosphere. Ozone occurs mainly at about 50,000 to 100,000 feet above the ground. It is subject to a wide seasonal variation, being most abundant in March and April, and least so in autumn ; concentrations are higher near the pole. Ozone has the power in summer of absorbing ultra-violet rays from the continuous sunlight very strongly, as well as some ordinary light and some longwave radiation from the earth's surface. It uses this absorbed energy to heat the polar stratosphere as the sun rises in spring. Later in the year, as the amount declines, the temperature falls, and with the vanishing of the sun, the arctic stratosphere drops to its intense winter cold. Two other gases, water vapour and carbon dioxide, also play a role in these changes. We shall see later how this great seasonal range of temperature creates even more spectacular events in the middle stratosphere.

The Ferrel vortex is subject to wide interannual variations, and to both long-and short-period disturbances, which are linked with the travel of the familiar cyclones and anticyclones at lower levels. These disturbances take the form of immense waves in the westerlies, some stationary and of low wavelength, others fast-moving and of short wavelength. Occasionally anti-cyclones build up through the entire troposphere and lower stratosphere, « blocking » the westerlies and disturbing the circulation over the whole arctic areas. At such times it is characteristic, as Flohn and Seidel have shown,[10] that the arctic area warms up, coldest conditions being displaced towards North America. These disturbances are beyond the scope of the present essay.

The stratospheric « monsoon »

At heights above about 65,000 feet, the arctic stratosphere displays a remarkable seasonal reversal of mean flow. It has been known since 1935 that winds at these levels over Europe reverse from westerly in winter to easterly in spring — an effect described by F. J. W. Whipple, who inferred the reversal from acoustical observations, as a stratospheric monsoon.[11] In some ways this term is apt, for the seasonal reversal of winds over the monsoon countries also results from great radiative changes between summer and winter. In the past few years we have been able to confirm the existence of these currents by direct observation, and to show that they arise from the same radiative causes as those discussed in the previous section.

The *polar-night vortex* of westerly winds becomes established at these levels in early September, increasing irregularly in strength to a maximum in December or early January, at least as far as mean values are concerned. We have only a hazy idea of the maximum strength, since sounding balloons are most often lost when winds are strong and temperatures cold. Probably the mean westerly flow much exceeds 60 mph. over a wide sub-polar belt at 80,000 to 100,000 feet. The poleward temperature gradient is considerable so that the winds increase with height at least to these levels.

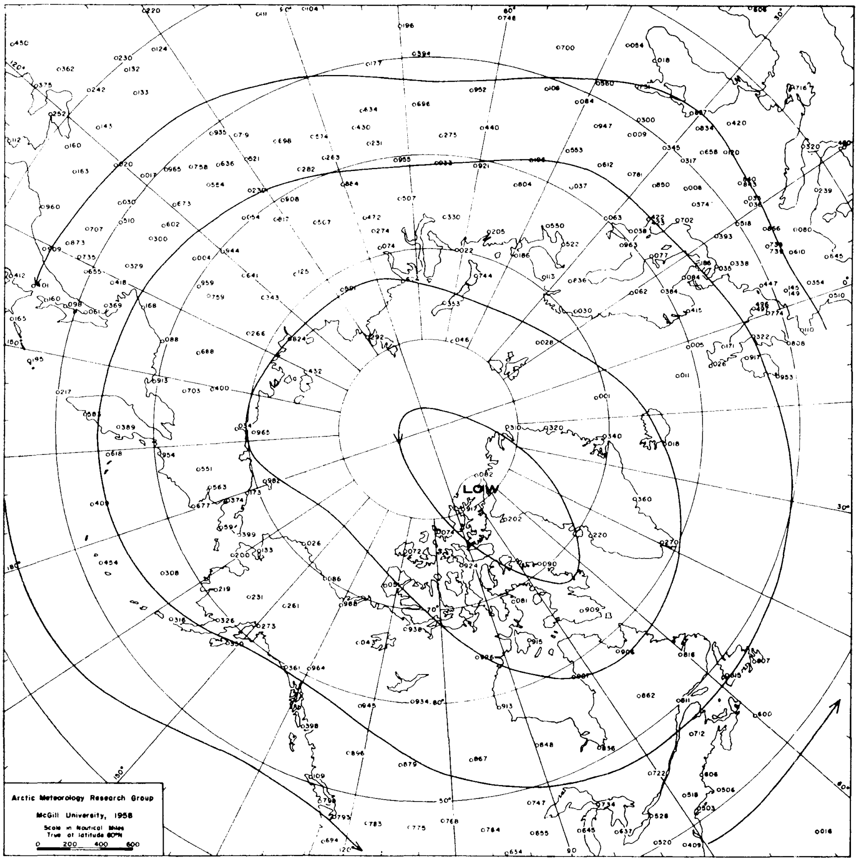
Though the polar-night vortex lies in the mean directly above the Ferrel vortex, the two are actually distinct in behaviour and origin. The most interesting discovery of the past three years has been that a strong jet-stream frequently

[10] Flohn, H., and Seidel, G., *Recent studies on the Arctic troposphere and its teleconnections*, in *Polar atmosphere symposium, Part I, Meteorology section*, R. C. Sutcliffe, editor, London, New York, Pergamon Press, 1958, pp. 62-70.

[11] Whipple, F. J. W., *Propagation of sound to great distances*, in *Quarterly Journal of the Royal Meteorological Society*, 1935, vol. 61, pp. 283-308.

JULY MID-TROPOSPHERE

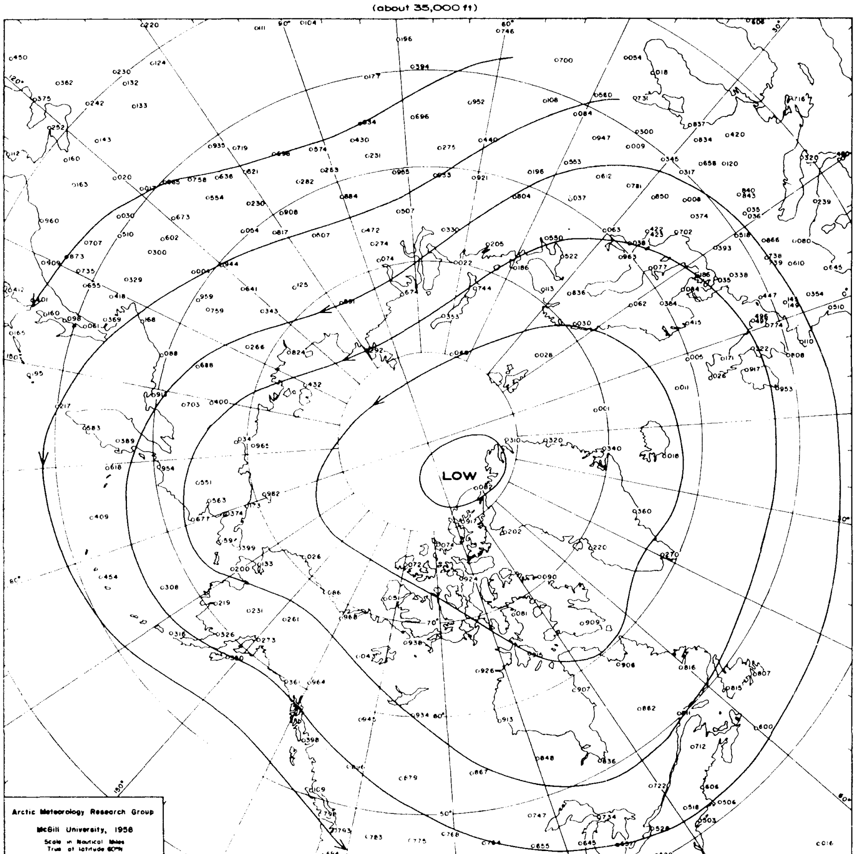
15-20,000 ft



I

JULY BASAL STRATOSPHERE

(about 35,000 ft)



II

FIGURE IV

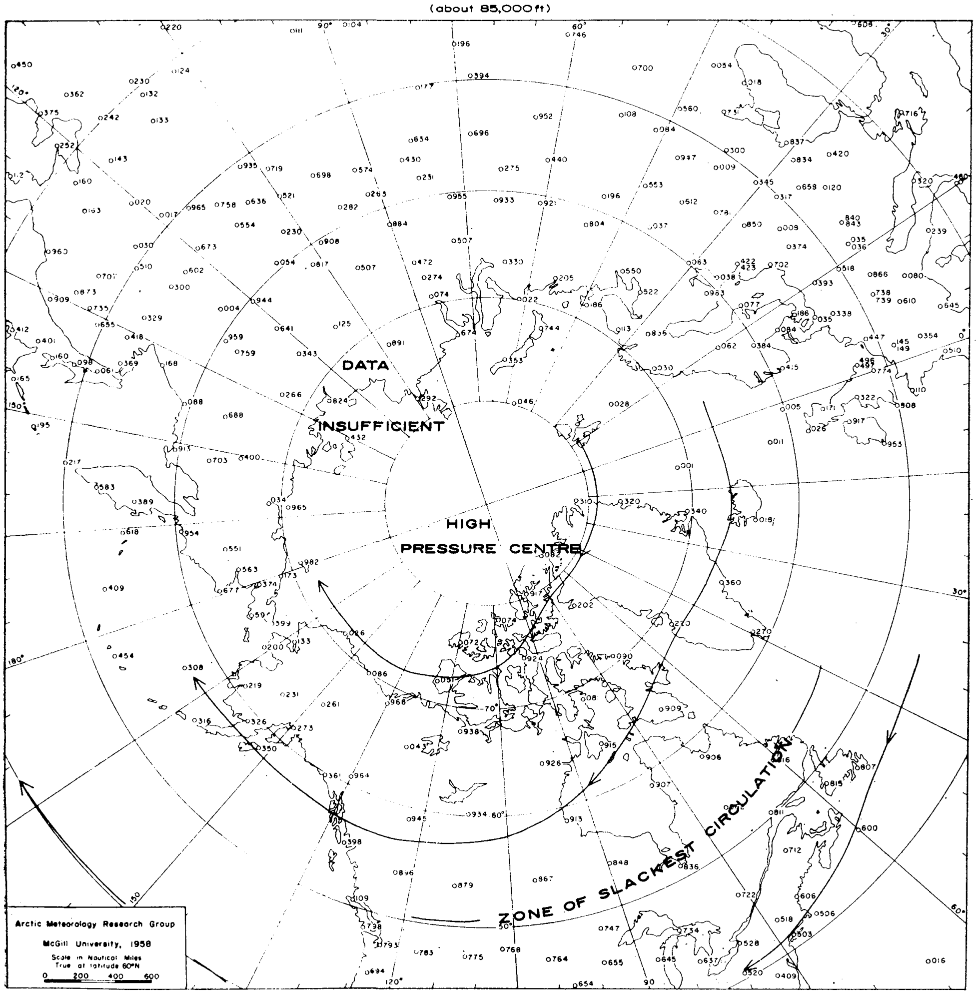
Sketches of the mean-flow-patterns of the Arctic atmosphere (*mid-summer*)

I. Middle Troposphere (15–20,000 feet)
II. Basal Stratosphere (about 35,000 feet)
III. Middle Stratosphere (about 85,000 feet)

Maps I and II show the Ferrel vortex, which is slacker and simpler in outline than that of figure II. Map III shows the easterlies of the middle stratosphere, that probably extends up to 150,000 feet.
Source as in figure II.

develops within the polar-night vortex. The polar-night jet has been shown to exceed 200 mph. at times, and to be centered at about the 80,000 ft. level. Lee and Godson,[12] who first described it, supposed that it blew approximately along the edge of the polar darkness, moving outwards as the autumn advanced. Later observation, however, has shown that its path is variable, and that successive

JULY MIDDLE STRATOSPHERE
(about 85,000 ft)



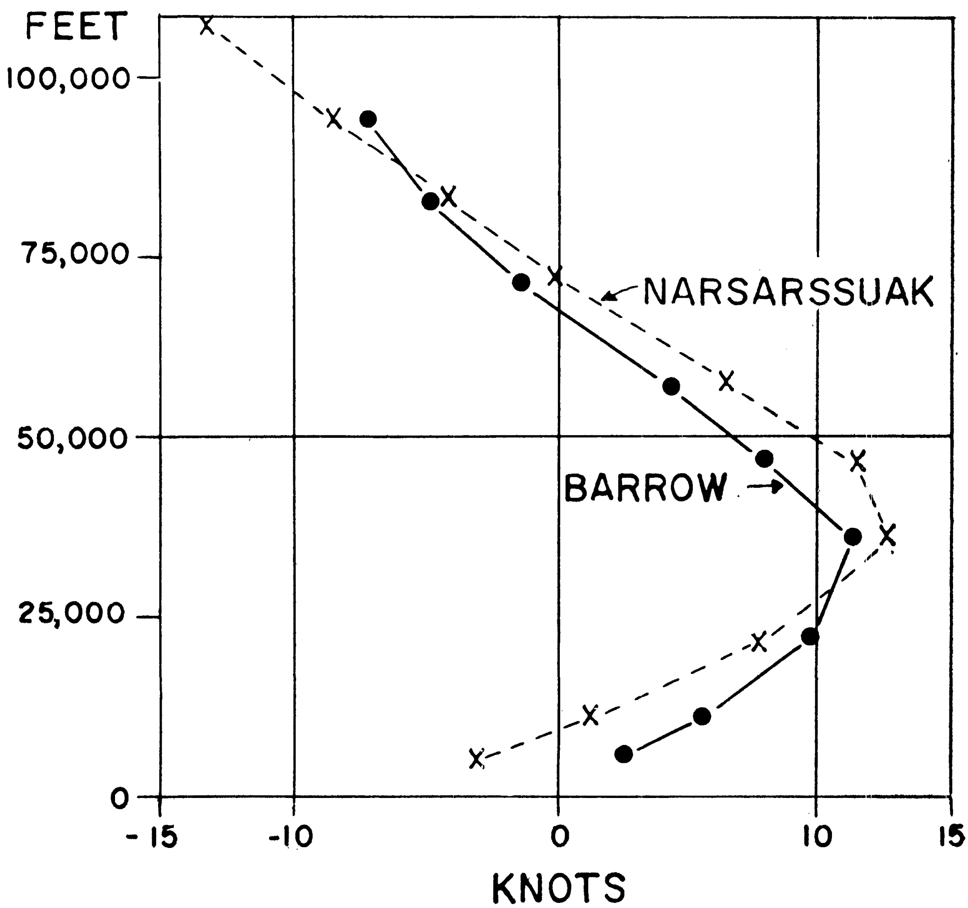
III

winters differ widely. Nevertheless, the polar-night jet-stream must be ranked one of the major discoveries of the aerological age. It is, of course, quite distinct from the mid-latitude jets, which occur at much lower levels.

[12] LEE, R., and GODSON, W. L., *The Arctic stratospheric jet stream during the winter of 1955-56*, in *Jour. Meteor.*, 1957, vol. 14, pp. 126-135.

The polar-night vortex is subject to large-scale disturbances of a kind rather different from those of lower levels, especially in the latter part of winter. These disturbances and their consequences — chiefly sudden rises of stratospheric temperature — are still imperfectly understood. The individual daily weather map in the middle stratosphere — at the 50 millibar or 25 mb. pressure levels,

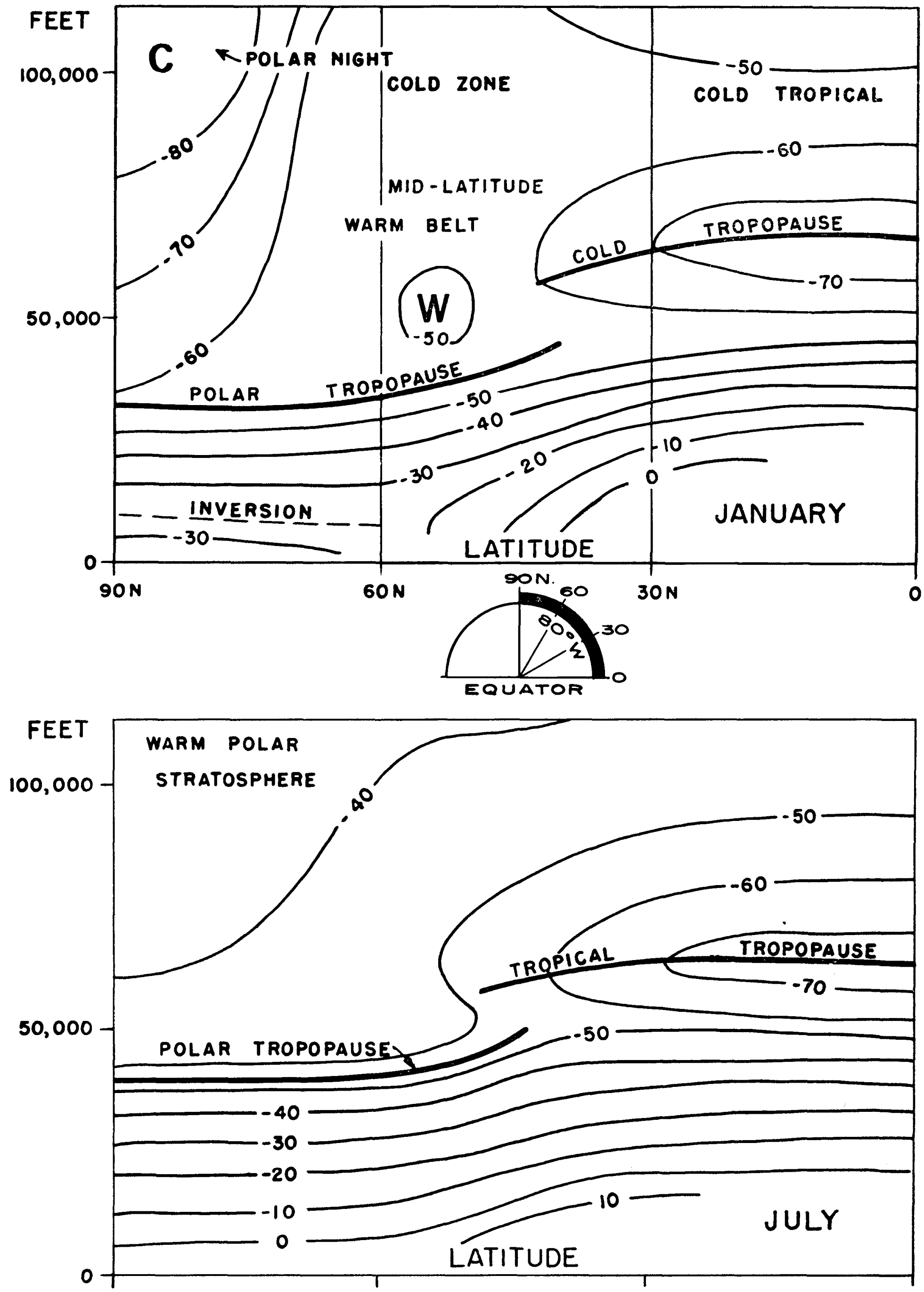
FIGURE V



Strength of the circumpolar westerlies over Barrow (71°N.), Alaska, and Narsarssuak (61°N.), Greenland, in summer. As measured by radio-tracked sounding ballons. N. B. Negative values indicate easterly winds, It will be observed that winds are easterly above 70,000 feet.

about 65,000 and 80,000 ft. respectively — usually shows, in mid-winter, one or more deep and extensive cyclones, the centres of which have temperatures below $-100°F$. The polar-night jets blow around these lows at some distance from the centre. At some time in the later winter, perhaps as early as January, there is a sudden collapse of these systems ; temperatures rise rapidly, sometimes by as

Figure VI



Mean temperatures along the 80°W meridian, January and July (degrees Centigrade). The great reversal of temperature gradient induced by the contrast between summer and winter in the arctic stratosphere is noteworthy. N. B. not standardized for period. Sources : Kechansky, south of 40°N. ; Original data N. of 60°N. ; composite 40-60°N.

much as 50°F. in a single day. At the same time the cyclones are replaced by flat, sprawling anticyclones separated by shallow troughs. Winter is effectively over. Nothing equivalent to these dramatic transformations is ever shown by the weather map at lower levels.

The causes of the sudden warmings remain obscure. From the fact that they show up first at the highest levels, Scherhag [13] and others have supposed that showers of solar corpuscular radiation falling into the atmosphere were responsible, and from the fact that such radiation is affected by the earth's magnetism inferred that the sudden warmings would be especially dramatic near the north magnetic pole in Arctic Canada — which is undoubtedly true. But no convincing arguments were produced to account for the effect, and today most authorities prefer to ascribe the sudden warmings to dynamic instability of some sort within the polar-night vortex itself. It has been shown by Craig and Hering [14] that the rises of temperature and the anticyclogenesis can be accounted for by general descent of air, with consequent compression and warming.

The spring and summer circulation at these levels is the reverse of the polar-night vortex. From May until mid-August — sometimes as early as March — the whole polar stratosphere is warm, and pressures are high. A large quasi-permanent anticyclone lies near the pole, and light but persistent easterlies encircle its flank (see Figure IV) down to mid-latitudes. In mid-summer the easterlies begin near the pole at about 60,000 ft., and above 90,000 ft. they are actually continuous with the strong sub-tropical easterlies. Thus at these high levels a single stable easterly entirely encircles the earth from pole to sub-tropics. Unlike the polar-night vortex, however, the summer easterly vortex is low in speed and very little disturbed.

In early August, strong cooling of the stratosphere begins, and by mid-month the easterlies are weakening fast. By the beginning of September the whole stratosphere above 65,000 ft. is disorganized, and is ready for the repetition of the cycle.

Conclusion

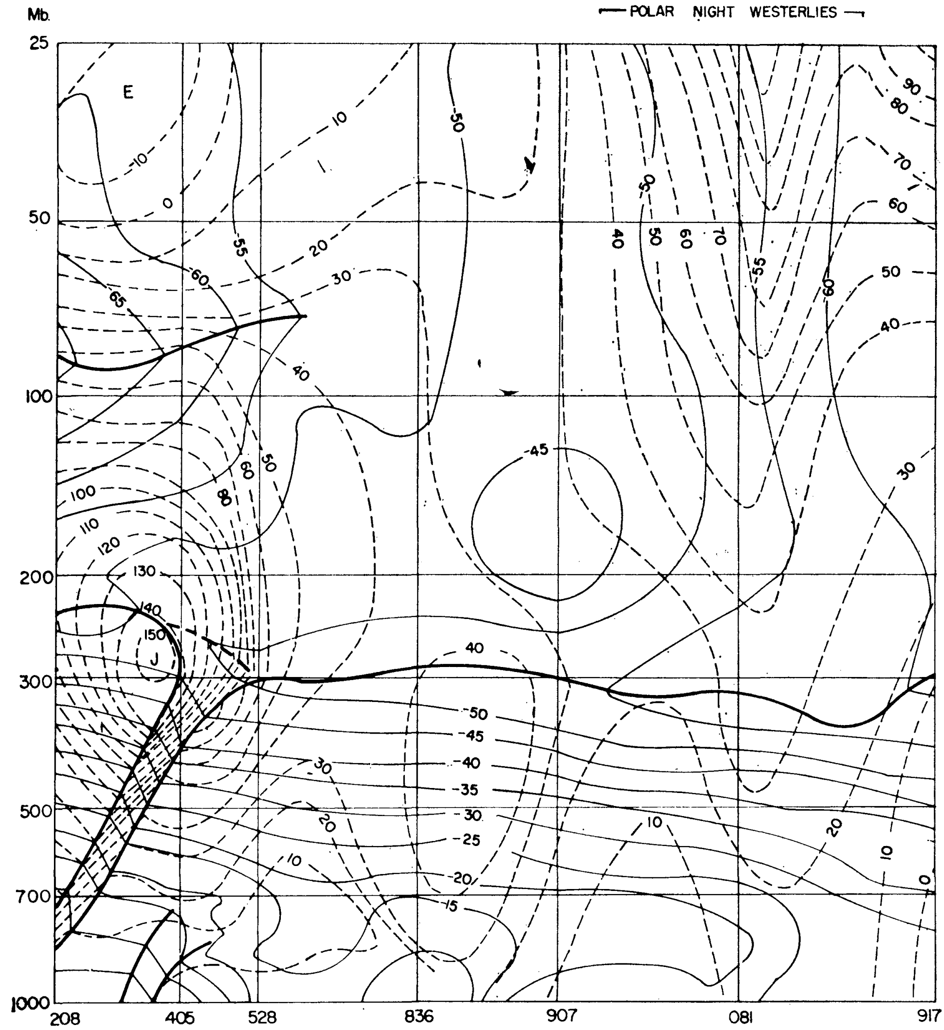
What bearing do these facts have on theories of climatic change? As yet one can hardly say. A few generalizations worth making are listed here :

(*i*) The modern arctic circulation is obviously *primarily* made up of the great vortices just discussed, which affect some 80% of the mass of the arctic atmosphere. Only in the bottom 20% does there emerge the familiar pattern so often invoked to account for present-day climates ; and, as we have seen, the surface patterns are in large measure functions : (*a*) of the circumpolar westerly vortex above ; and (*b*) the existing ephemeral disposition of land, sea, ice and mountain. It is hence unlikely that we can find an adequate theory of climatic

[13] Scherhag, R., *Die explosionsartigen Stratorpbärenerwarmungen des Spätwinters 1951-52*, in *Ber. Deutsch. Wetterdienst, in der U. S. Zone*, vol. 6, pp. 51-63.

[14] Craig, R. A., and Hering, W. S., *An « Explosive warming » at 25 mb. in January, 1957*, in *Technical Memorandum No. TM-57-17*, Geophysics Research Directorate, Air Force Cambridge Research Center, Cambridge, Mass., 1957.

FIGURE VII



Vertical cross-section through atmosphere along a line Charleston (208) — Washington (405) — Buffalo (528) — Moosonee (830) — Port Harrison (907) — Hall Lake (081) — Eureka (917). Lines of constant westwind speed (blown toward reader), with values in knots, are dashed. « J » is the jet-stream and « E » indicates the subtropical easterlies of the stratosphere. The Ferrel and Polar Night westerly systems are very distinct. Isotherms are in solid lines (degrees Celsus). Heavy black lines are the tropopause. Note the Polar Front extensions down below jet-stream.

variation unless we can account for the present-day behaviour of the Ferrel vortex, and probably of the higher vortices as well.

(*ii*) Efforts to account for climatic variation by invoking extra-terrestrial impulses — changes in the solar constant, or in the frequency of showers of corpuscular radiation — cannot come to grips with the above problem, since we do not yet understand the relationship between the earth's heat balance and the behaviour of the circumpolar vortices. Thus Willett's [15] well-known attempts to prove a relationship between sunspot activity and modern climate have had to rely on very crude correlations with observed precipitation, pressure distribution at sea-level and temperature at sea-level.

(*iii*) The circulations affecting the arctic, as described above, are merely parts of the wider general circulation of the entire earth, or at least the northern hemisphere. One can hope to explain them in ordinary cause-and-effect terms only when the general circulation as a whole has yelded to such treatment. And this time is as yet distant.

Climatology is a field in which speculation tends to run far ahead of established knowledge and well-founded theory. In large part this arises from the fact that the complexities of the existing circulation, and of its mechanisms, are inadequately realized. The writer believes that dynamic climatology as a field of research offers the real key to an understanding of the vast problem of climatic variation. Until we have explored, described and theoretically explained contemporary climates, there is little hope that we can deal with those of the past.

[15] WILLETT, H. C., *The general circulation of the last (Würm) glacial maximum*, in *Geografiska Annaler*, 1950, vol. 32, pp. 179-187.